Argonne National Laboratory

LAMB WAVES: THEIR USE IN NONDESTRUCTIVE TESTING

by

Roberta Ann di Novi

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LAMB WAVES: THEIR USE IN NONDESTRUCTIVE TESTING

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I. INTRODUCTION

The theoretical aspects of Lamb waves and the experiments which verified their basic properties were described in a previous report.* The present status report will describe a series of experiments conducted as part of the research program of the Nondestructive Testing Group of the Metallurgy Division of Argonne National Laboratory, and which was primarily concerned with establishing the usefulness of Lamb waves for the detection of small defects in thin plates and in small-diameter, thin-walled tubing.

II. THEORETICAL ASPECTS

Several characteristics of Lamb waves will be qualitatively described to provide a background for the experimental discussion. Lamb waves consist of an infinite number of modes of vibration that can be generated in elastic materials. Lamb's grouping of these infinite number of modes into symmetric and asymmetric depends on the direction of the particle displacement and is of no practical importance.

In a given material, each Lamb wave mode has a different velocity of propagation. The phase velocity with which each mode travels is dependent on the thickness of the plate, the frequency of the wave, the order of the mode, and the material in which the wave is generated. Figures 1a and 1b illustrate the phase velocity - frequency-thickness (fd) relationship in aluminum for the symmetric and asymmetric types of motion. For a given fd product, there are a finite number of modes that can be generated, and the number of possible modes increases as the fd product increases. For example, in aluminum at an fd product of 2×10^5 in./sec, three symmetric and three asymmetric modes can be generated, wheareas at an fd product of 5×10^5 in./sec, six symmetric and six asymmetric modes can be generated. In the first case, if the frequency is 5 Mc, a thickness of 40 mils is required to satisfy the fd condition. Obviously, then, thin materials are the most suitable for the generation and detection of Lamb waves at ultrasonic frequencies.

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*di Novi, Roberta Ann, Status Report on Lamb Waves, ANL-6329 (March 1962).
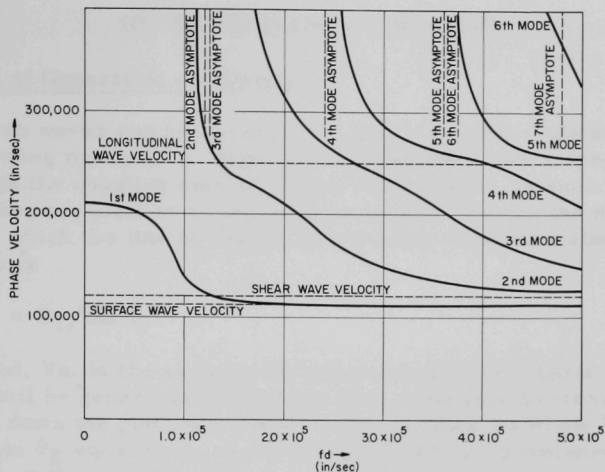
Fig. 1a. Waves in Aluminum Plate, Symmetrical Type;
Phase Velocity Plotted against Product of
Frequency and Plate Thickness.

Fig. 1b. Waves in Aluminum Plate, Asymmetrical Type;
Phase Velocity Plotted against Product of
Frequency and Plate Thickness.
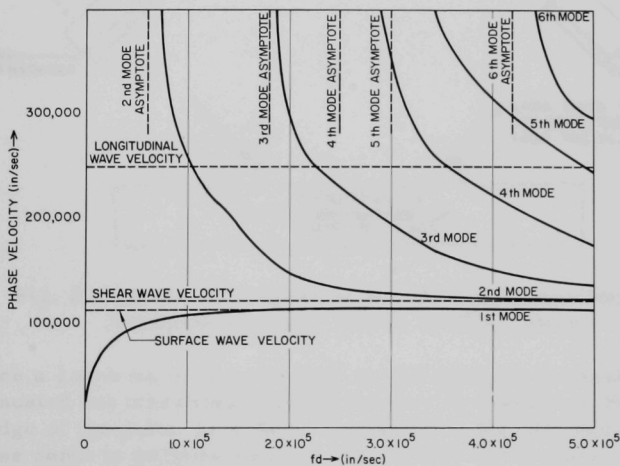
III. EXPERIMENTAL ASPECTS

A. Method of Generation and Detection

Lamb waves can be generated in thin materials - plates or tubing - in the following manner. A longitudinal sound wave with a speed V_L is sent through the coupling medium, water for example, in such a manner that it strikes the plate at an angle θ_i, as measured from the normal. The speed with which the line of contact of any wave front runs along the surface of the plate is

$$Va = V_L / \sin \theta_i \quad . \tag{1}$$

If this speed, Va, is the same as the phase velocity of a Lamb wave mode, the mode will be generated in the plate by a resonance process. The wave will travel down the plate and radiate from it, along its whole length, with an exit angle θ_E equal to θ_i. A receiving transducer positioned at the angle θ_E will detect this energy. This received pulse can then be amplified and displayed. Figure 2 shows the typical arrangement of transducers and specimen for the generation and detection of a Lamb wave mode.
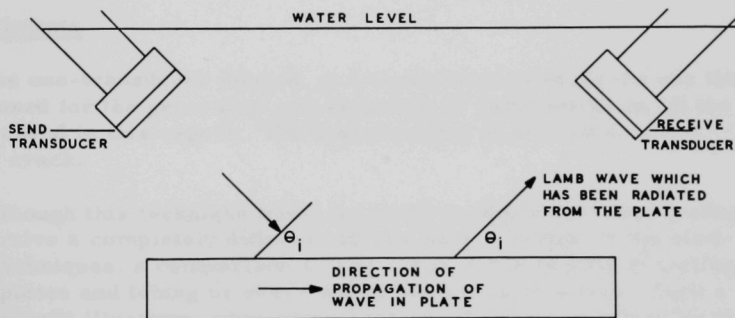
Fig. 2. Typical Arrangement for the Generation and
Detection of Lamb Waves in Thin Plates.

Once a Lamb wave is generated, it will continue to travel down the plate, attenuated but otherwise undisturbed until it reaches a discontinuity, e.g., the edge of the plate, or a flaw. Assume that the discontinuity is a crack whose depth is perpendicular to the surface of the plate. Then, the fd product is no longer satisfied over this crack, and the Lamb wave mode will not appear over this crack. A receiver aimed at this flaw area will indicate its presence by the absence of a signal. It is also possible to detect this crack with one transducer as both sender and receiver. In this situation, no signal is received until the Lamb wave reaches a discontinuity.

The mode is, in part, "reflected" from the discontinuity and travels back along the plate. It also is radiated from the plate at an exit angle θ_E equal to θ_i, and can then be detected by the same transducer that was used to generate it.

B. Equipment

All tests were made with a standard Sperry (Type UR) Reflecto-scope; it was used in conjunction with a Sperry Recording Attachment Type R.A. Strip-chart recordings were made with an Offner Dynograph Amplifier-Recorder.

The transducers used for the experiments with the plates were Sperry Immersion Testing Search Units, Style 50A1338, Type SI. They are 5-Mc quartz transducers having a $\frac{3}{8}$-in. diameter. The transducers used for the tests on the tubing were Curtiss-Wright Hi-R units. They are a 5-Mc lithium sulfate transducer having a $\frac{7}{8}$-in. diameter. Angular settings of the transducers up to 35° are made by means of a Curtiss-Wright Precision Manual Manipulator. These settings are read on quadrant-type scales with magnifiers. The system is accurate to ±0.5°.

C. Experiments

The one-transducer method, previously described, is the one that has been used for the generation and detection of Lamb waves in all the work discussed in this report. The discontinuity, in all cases, was a simulated crack.

Although this technique itself is identical with shear wave testing, it does involve a completely different stress wave. In view of the similarity of techniques, a comparison will be made of the results of testing the same plates and tubing by shear waves and by Lamb waves. Such a comparison will illustrate, what advantages, if any, may be gained by the use of Lamb waves.

1. Experiments on Plates

The first set of specimens were six aluminum (1100) plates, 4 in. x 12 in. x 0.033 in. Simulated cracks were cut into these plates (see Figure 3). These were 2 in. long, 0.032 in. wide, and had depths of 0.001 in., 0.002 in., 0.003 in., 0.006 in., and 0.009 in.

At 5 Mc, the fd product is 1.65×10^5 in./sec, and the modes indicated in Table I can be generated at the indicated angles of incidence.
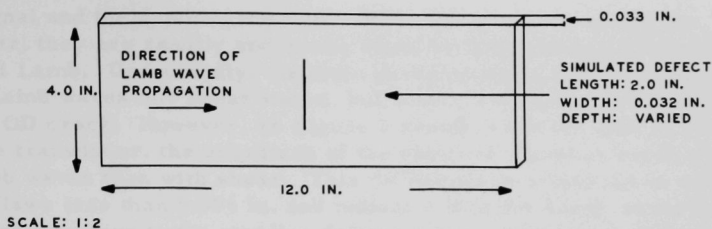
Fig. 3. Orientation of Simulated Crack with Respect to the Plate.

Table I

ANGLES OF INCIDENCE REQUIRED TO GENERATE
LAMB WAVE MODES IN ALUMINUM
($fd = 1.65 \times 10^5$ in./sec)

Mode	Angle of Incidence (θ_i)	Phase Velocity V_p, in./sec x 10^{-5}
1A	32° 3'	1.10
1S	31° 46'	1.13
2A	19° 51'	1.72
2S	14° 42'	2.30
3S	7° 8'	4.7

The closeness of the angles of incidence make the 1A and 1S modes experimentally indistinguishable. They are referred to as the 1A-1S mode. It should also be noted that the angle of incidence necessary to generate surface or Rayleigh waves is 31° 25'. Experimentally, Rayleigh waves and the 1A-1S modes are also indistinguishable. No tests were made at 7° 8'; at this small angle, the front surface reflection interferes with the flaw "reflection," and the two cannot be reasonably separated. Shear waves can be generated at angles up to the critical angle θ_c (shear) = 28° 35'. Two angles, 22° and 26°, at which only shear waves can be generated were selected for the shear-wave tests.

Figure 4 shows the amplitude of the flaw "reflection" versus the depth of the flaw. The flaws are facing the transducer, i.e., there is an OD defect. Figure 5 illustrates the amplitude of signal versus depth in the case when the flaws are turned away from the transducer, i.e., there is an ID defect. In all cases, we are dealing with an ideal situation, as the flaw depth is always orientated perpendicularly to the surface of the plate. In Figure 4 can be seen a direct correlation between the amplitude

of the signal and the depth of the flaw. When the flaws are facing the transducer, they are readily and easily found by both types of wave motion - shear and Lamb. Undoubtedly, the main phenomenon in operation here, is neither Lamb waves nor shear waves, but rather a direct surface reflection from the OD crack. However, as Figure 5 shows, when the flaw is not facing the transducer, the amplitude of the received signal is much greater with Lamb waves than with shear. This difference in amplitude is considerable for flaws less than 0.006 in. and indicates that the Lamb waves are much more sensitive to the smaller defects. After this series of tests was completed, the defects of nominal depth 0.001 in. and 0.002 in. were measured to obtain a more accurate value. They were found to be actually 0.0004 in. and 0.0014 in., respectively.

Fig. 4. Amplitude of Lamb-wave and Shear-wave Flaw Signals versus Depth of Flaw for Two-inch-long Outer Surface Cracks in Plates.

To achieve a more realistic condition, additional specimens with smaller flaws were prepared. These were made with an Elox arc-discharge cutter and had 0.002-in. widths and 1.0-in. lengths. Again, the depths varied from 0.001 in. to 0.009 in. The depths of these were also oriented perpendicularly to the surface of the plate. The amplitude of the flaw "reflection" versus depth of the flaw is shown in Figure 6 for the flaw facing the transducer configuration, and in Figure 7 for the flaw turned away from the transducer configuration. Figure 7 also illustrates the greater sensitivity that can be achieved by means of Lamb waves. (The gain of the electronic equipment was at a higher level in this last two series of tests.)
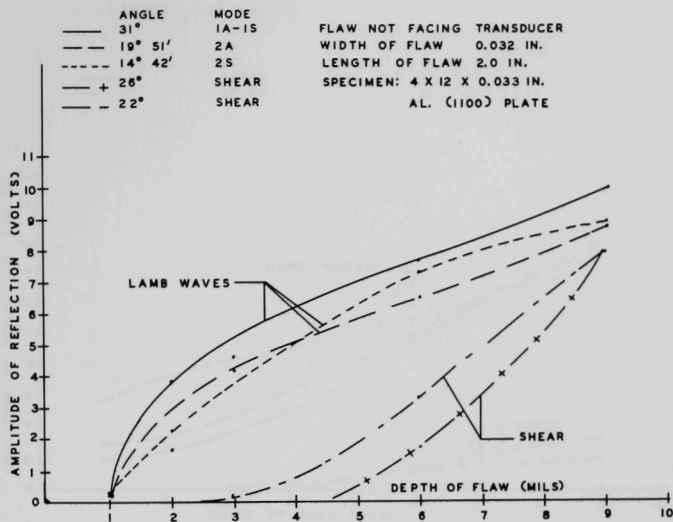
Fig. 5. Amplitude of Lamb-wave and Shear-wave Flaw
Signals Versus Depth of Flaw for Two-inch-long
Inner Surface Cracks in Plates.
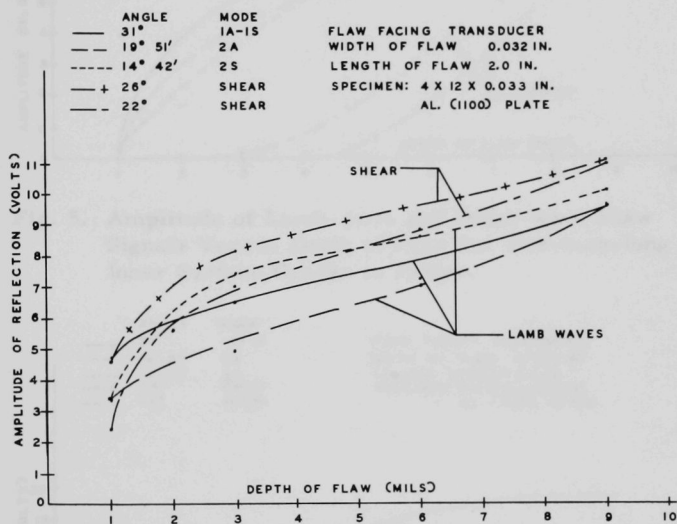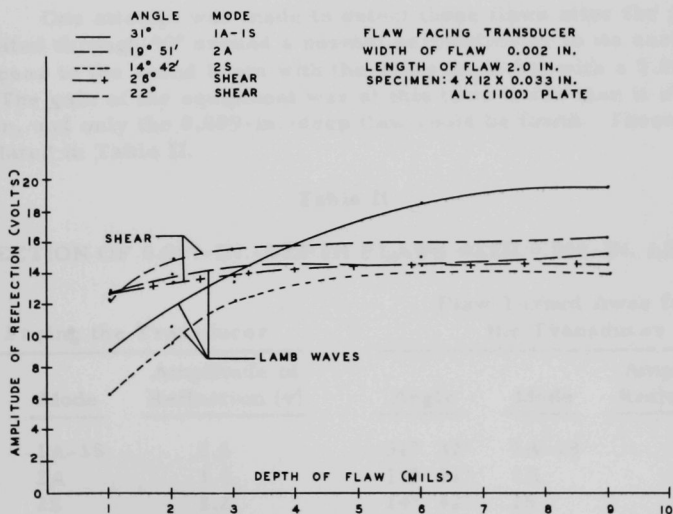

Fig. 6. Amplitude of Lamb-wave and Shear-wave Flaw
Signals Versus Depth of Flaw for One-inch-long
Outer Surface Cracks in Plates.
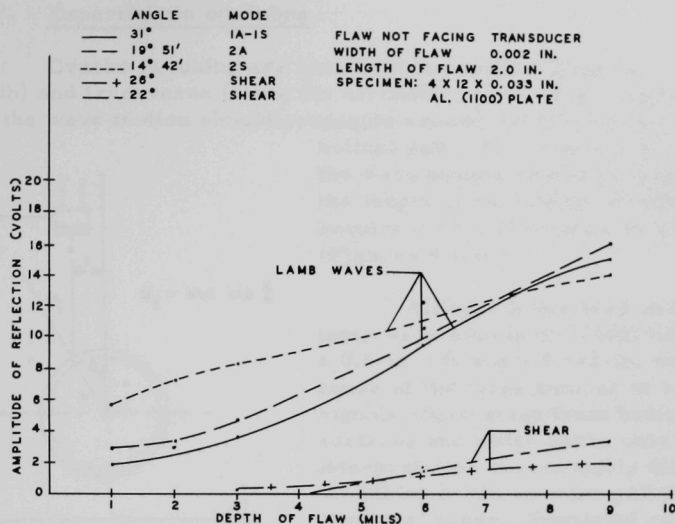
Fig. 7. Amplitude of Lamb-wave and Shear-wave Flaw
Signals Versus Depth of Flaw for One-inch-long
Inner Surface Cracks in Plates.

One attempt was made to detect these flaws after the plate had
been rotated through 90° around a normal perpendicular to its surface. The
flaws appear to the sound beam with the same depth but with a 0.002-in.
length. The gain of the equipment was at this time lower than it should
have been, and only the 0.009-in.-deep flaw could be found. These results
are tabulated in Table II.

Table II

DETECTION OF 0.009-IN.-DEPTH FLAWS WITH 0.002-IN. LENGTH

Flaw Facing the Transducer			Flaw Turned Away from the Transducer		
Angle	Mode	Amplitude of Reflection (v)	Angle	Mode	Amplitude of Reflection (v)
31° 32'	1A-1S	2.6	31° 32'	1A-1S	2.50
19° 51'	2A	3.0	19° 51'	2A	2.45
14° 42'	2S	3.2	14° 42'	2S	2.6
26°	Shear	2.7	26°	Shear	*
22°	Shear	2.9	22°	Shear	*

*No received signal

2. Experiments on Tubes

Cracks in tubing are ideally of two types: longitudinal (along the length) and transverse (along the circumference). For longitudinal cracks, the wave motion should propagate around the tube, actually in a helical path. For transverse cracks, the wave motion should propagate down the length of the tubing. These conditions require different transducer placements (Figures 8 and 9).

All specimens used in this set of tests were aluminum (1100) tubing with a 0.5-in. OD and a 0.032-in. wall. Because of the large number of spurious signals which arise from badly finished surfaces and which serve only to make interpretation unreasonably difficult, the tubing surfaces were polished with jewelers' rouge. Simulated cracks were made in the OD by means of a discharge cutter, and transverse flaws in the ID by means of a specially designed cutting tool which fits into the tube. This device, although useful, does have the disadvantage that neither the depth of cracks nor the uniformity of the depth can be controlled.

Fig. 8. Arrangement for the Detection of Longitudinal Defects in Tubing.

$$\Theta_i = \text{ARC SIN } \frac{x}{R}$$

a. Longitudinal Flaws

The first set of flaws made were 0.032 in. wide, 0.5 in. long, and had depths of 0.009 in., 0.006 in., 0.003 in., 0.002 in., and 0.001 in. Table III shows the amplitude of the received signal for each flaw at Lamb and shear wave angles.

Fig. 9

Arrangement for the Detection of Transverse Defects in Tubing.
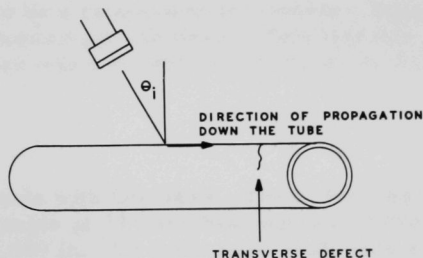
Table III

AMPLITUDE OF FLAW SIGNAL FOR OD LONGITUDINAL CRACKS

Angle	Mode	Amplitude (v) for Cracks of Depths				
		0.001 in.	0.002 in.	0.003 in.	0.006 in.	0.009 in.
31° 32'	1A-1S	5.6	9.0	9.2	13.0	16.0
19° 51'	2A	5.0	9.6	12.0	12.5	14.5
14° 42'	2S	5.6	7.4	11.0	13.0	15.0
26°	Shear	5.6	7.2	8.8	12.0	16.8
22°	Shear	5.0	8.4	13.8	12.5	16.5

From the work that had been done on plates, these general results were to be expected. However, it was noticed that a flaw signal was obtained regardless of the angle of incidence ($14° \leq \theta_i \leq 32°$) that was chosen.
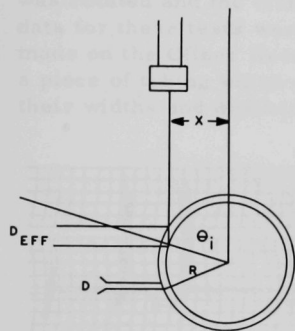

It appears that, with this transducer configuration, it is impossible to define a thickness for the tubing. To get an angle of incidence θ_i, the transducer is moved a distance x (see Figure 10). But, when the transducer is moved off the radius, the center of the transducer no longer is over a thickness d, but an effective thickness d_{eff} which is larger than the d used in the calculation for fd. The d_{eff} is also a function of x. Also, each portion of the beam sees a different d_{eff}. This, coupled with the beam spread, makes for a wide range of incidence angles and fd products for each value of x. These factors are thought to be the cause for the reception of a flaw signal regardless of the incidence angle.

Fig. 10. d_{eff} in Relation to d.

Undoubtedly, there could be a refinement of technique, for example, by suitable masking and collimating of the beam. This was not tried at the time, and no further work was done with Lamb waves on this type of flaw.

b.   Transverse Flaws

One set of tests were made with OD flaws. These were about 0.002 in. wide, subtended a central angle of 70°, and had depths of 0.001 in., 0.002 in., 0.003 in., 0.006 in., and 0.009 in. All tests were made with a rectangular ($\frac{1}{4}$ x $\frac{1}{8}$-in. opening) mask on the sender-receiver transducer.

The results agreed with that obtained for plates and for longitudinal flaws, and are tabulated in Table IV.

Table IV

AMPLITUDE OF FLAW SIGNAL FOR OD TRANSVERSE CRACKS

		Amplitude of Flaw Signal (v) for Various Flaws of Depths				
Angle	Mode	0.001 in.	0.002 in.	0.003 in.	0.006 in.	0.009 in.
31° 32'	1A-1S	17.0	19.0	21.0	21.0	*
19° 51'	2A	21.5	21.0	21.0	20.0	19.5
14° 42'	2S	*	19.0	18.5	19.0	19.0
26°	Shear	18.0	19.0	18.5	20.0	*
22°	Shear	19.0	19.3	19.0	18.5	20.0

*No reading was taken

The tests on the ID flaws were made dynamically, i.e., the tube was rotated and the transducer was translated parallel to the tube. The data for these tests were presented in the form of strip charts which were made on the Offner Recorder. Figures 11a and 11b are the strip charts of a piece of tubing which contained four ID transverse flaws. Table V gives their widths and depths; they subtended a 60° central angle.
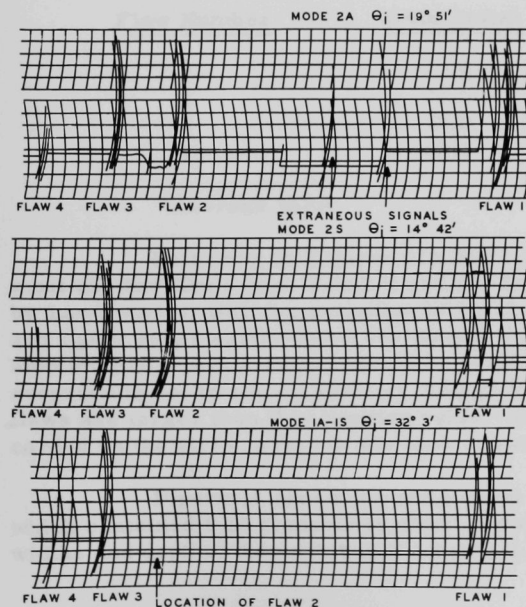

Fig. 11a

Detection of ID Transverse Simulated Cracks by Means of Lamb Waves and Shear Waves.
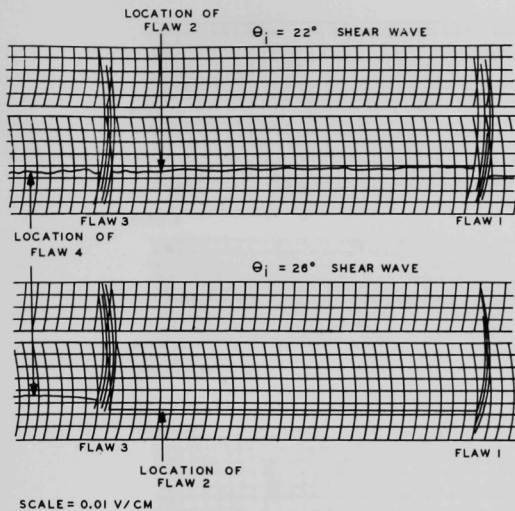
SCALE = 0.01 V/CM.

Fig. 11b.

Detection of ID Transverse Simulated Cracks by Means of Lamb Waves and Shear Waves.

Table V

DIMENSIONS OF ID TRANSVERSE CRACKS

Flaw Number	Width (mils)	Depth* (mils)
1	22.0	5.9
2	31.0	0.676
3	46.0	4.83
4	45.0	0.88

*Average value

Referring to Figures 11a and 11b, it can be seen that the two most shallow flaws (nos. 2 and 4) are not detected by shear waves, but are by Lamb waves, with the exception of No. 2 at $\theta_i = 32° 3'$. Both shear waves and Lamb waves easily detect the deeper cracks. No comparison of the amplitude of the flaw signal should be made for the deeper flaws as the recorder is set to record limiting voltage V, and all signals for the deeper flaws are larger than this limiting value. The same amplitude will be recorded on the strip chart for any flaw signal $v \geq V$.

Figure 12 shows the strip chart recordings for a piece of tubing which contained 8 ID transverse simulated cracks. Table VI gives their widths and depths; they subtended a central angle of 60°.
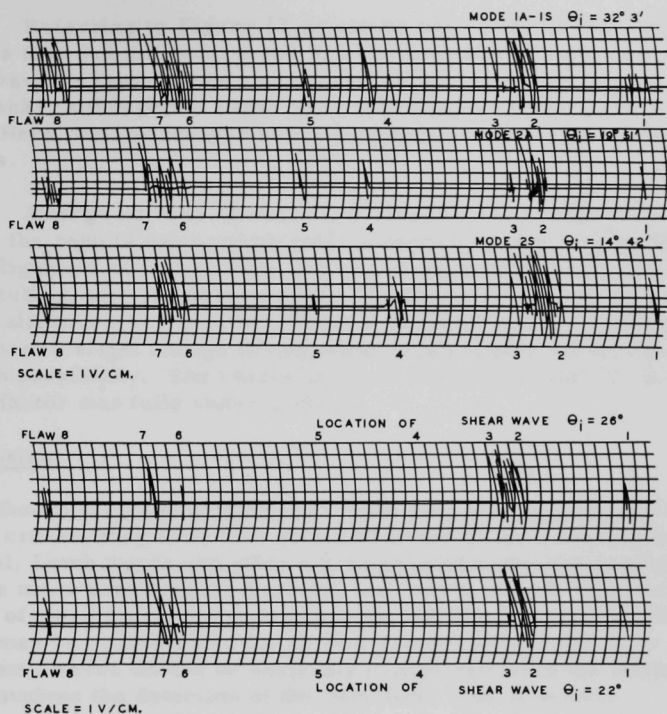
Fig. 12. Detection of ID Transverse Simulated Cracks by Means of Lamb Waves and Shear Waves.

Table VI

DIMENSIONS OF ID TRANSVERSE CRACKS

Flaw Number	Widths (mils)	Depth* (mils)
1	23.4	1.49
2	62.5	3.66
3	31.2	1.09
4	15.6	0.73
5	15.6	0.94
6	31.2	1.06
7	46.8	4.34
8	23.4	1.55

*Average value

Referring to Figure 12, it can be seen that the two flaws with depths less than 1.0 mil (nos. 4 and 5) were detected by Lamb waves but not by shear waves. Lamb waves and shear waves serve equally well on the deeper cracks, although the Lamb wave indications appear more pronounced. Here, too, no comparison should be made of the strip chart amplitudes.

A large number of such tests were made on tubing. In many instances, the results were not as clearly defined as they are in Figures 11 and 12. Alignment of transducers and specimen is most critical in the testing of tubing; this problem is only intensified with the use of Lamb waves. With poor alignment in a run, not even the deepest cracks could be detected. Furthermore, a slight change in alignment between runs made reproducibility an impossibility. The charts shown in Figures 11 and 12 were made when this factor was fully under control.

D. Conclusion

Although all these experiments were done with specimens that had simulated cracks, they have still demonstrated that, as a nondestructive testing tool, Lamb waves can offer a greater sensitivity and resolution than do the more conventional methods, i.e., shear waves. The main disadvantage of using Lamb waves in practice, namely, the critical alignment problem, may be compensated for by this greater sensitivity. For this reason, Lamb waves should be seriously considered when the testing problem involves the detection of the "smaller" type of defects.

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